HYDRODYNAMICS AND HIGH-ENERGY PHYSICS OF WR COLLIDING WINDS

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ABSTRACT

The stellar winds flowing out of the components of WR + OB binaries can collide and the shock waves are formed. Stellar wind collision, particle acceleration by the shocks and generation of X-ray, γ-ray, radio and IR emission in WR + OB binaries are discussed.

1. INTRODUCTION

One of the main properties of Wolf-Rayet (WR) stars is a very intense outflow of gas. The mass-loss rate for WR stars, $\dot{M}_{WR}$, and the terminal velocity of the matter outflow, V^{∞}_{WR}, far from the star amount to $\sim (0.8-8)\times 10^{-5}\ M_{\odot}$ yr^{-1} and $\sim (1-5)\times 10^{3}$ km s^{-1}, respectively (Willis 1982; Abbott et al. 1986; Torres, Conti and Massey 1986). No less than 40% of WR stars belong to binary systems. Young massive O and B stars are the secondary components of such systems. OB stars also have an intense stellar wind: $\dot{M}_{OB}\sim 10^{-6}\ M_{\odot}$ yr^{-1}, $V^{\infty}_{OB}\sim (1-3)\times 10^{3}$ km s^{-1} (Garmany and Conti 1984; Leitherer 1988).

If the intensities of the stellar winds of WR and OB stars are more or less comparable or if the distance D between the components of the binary is large enough (see below), the winds flowing out of WR and OB stars can collide and the shock waves are formed. In the shock the gas is heated to temperature $\sim 10^{7}$ K and generates X-ray emission (Prilutskii and Usov 1975, 1976; Cherepashchuk 1976; Cook, Fabian and Pringle 1979; Bianchi 1982; Luo, McCray and Mac Low 1990; Usov 1990; Stevens, Blondin and Pollock 1992; Usov 1992; Myasnikov and Zhekov 1993)

Until now X-ray emission from a few tens WR stars has been detected (Seward et al. 1979; Moffat et al. 1982; Caillaut et al. 1985; Pollock 1987). From the observational data it follows that the WR binaries are significantly brighter in X-rays than single stars (Pollock 1987), and the WR stars detected in X-rays have a much higher than usual incidence of binaries (Abbott and Conti 1987). These two facts can be naturally explained if the X-ray emission of WR binaries is enhanced essentially by the radiation of the gas heated in the shock. Besides, the analysis of the energy spectra of the X-ray emission and the time variability indicates that the X-rays are generated in the outer regions of the stellar wind near the OB star (Moffat et al. 1982; Pollock 1987; Williams et al. 1990), as expected in the model of stellar wind collision (see Section 2).

Stellar wind collision may be responsible not only for the X-ray emission of WR + OB binaries and for their radio, IR and γ-ray emision as well (Williams, van der Hurcht and Thé 1987; Williams et al. 1990, 1992, 1994; Usov 1991; Eichler and Usov 1993). Below, the gas flow, stellar wind collision, particle acceleration, and generation of X-ray, γ-ray, radio and IR emission in WR + OB binaries are discussed.

2. STELLAR WIND COLLISION IN WR + OB BINARY

2.1 *Stellar wind parameters*

For a typical WR + OB binary ($\dot{M}_{WR} \simeq 2 \times 10^{-5} M_{\odot}\mathrm{yr}^{-1}$, $\dot{M}_{OB} \simeq 10^{-6} M_{\odot}\mathrm{yr}^{-1}$, $V^{\infty}_{WR} \simeq V^{\infty}_{OB} \simeq 2 \times 10^3\,\mathrm{km\,s^{-1}}$, the distance between the components of the binary $D \simeq 10^{13}$ cm, the stellar wind gas temperature $T \simeq 3{\times}10^4$ K) the parameters of the gas ahead of the shock fronts are the following: The gas density $\rho \simeq 10^{-14}$ g cm^{-3}, the sound speed $V_s \simeq 10$ km s^{-1}, the free path length of charged particles $l \simeq 10^2$ cm, the Mach number $\xi = V^{\infty}_{WR}/V_s \simeq 10^2 \gg 1$, and the Reynolds number $\Re = (r_{OB}/l)\, m \simeq 10^{12}$. The free path length of particles and the Reynolds number behind the shoch fronts are $\sim 10^9$ cm and $\sim 10^3$, respectively. The above values of $\Re$ suggest that the gas flow is non-viscous and non-heat conductive.

2.2. *Geometry of the region of stellar wind collision*

The winds from the binary components are highly supersonic and flow nearly radially out to the shocks. In the shock the gas is heated to the temperature

$$T(V_{\perp}) = \frac{2(\gamma - 1)}{(\gamma + 1)^2}\,\frac{\mu}{k}\, m_p V_{\perp}^2 \simeq 3 \times 10^7 \left(\frac{V_{\perp}}{10^3\ \mathrm{km\,s^{-1}}}\right)^2\ \mathrm{K}\,, \qquad (1)$$

where γ is the ratio of heat capacities at constant pressure and at constant volume, $\mu{=}A/(1 + Z)$ is the mean molecular weight, A is the atomic weight of ion, Z is its electrical charge, k is the Boltzmann constant, m_p is the proton mass, and $V_{\perp}$ is the component of the stellar-wind velocity perpendicular to the shock front. The value γ is equal to 5/3 for a rarefied totally-ionized plasma. If helium predominates in the gas of the WR stellar wind, we have $A = 4; Z = 2; \mu = 4/3$.

Behind the shock the hot gas outflows from the region of stellar wind collision nearly along the contact surface (see in detail Usov 1992).

In the case of the collision of two spherical winds with the terminal velocities the distances r_{WR} and r_{OB} from WR or OB stars, respectively, to the region where these winds meet is

$$r_{WR} = \frac{1}{1 + \eta^{1/2}} D, \qquad r_{OB} = \frac{\eta^{1/2}}{1 + \eta^{1/2}} D \qquad (2)$$

(see Fig. 1), where

$$\eta = \frac{\dot{M}_{OB} V^{\infty}_{OB}}{\dot{M}_{WR} V^{\infty}_{WR}}\,.$$

Since $\dot{M}_{OB} \sim (0.01 - 0.1)\dot{M}_{WR}$ and $V^{\infty}_{OB} \sim V^{\infty}_{WR}$, the dimensionless parameter η is small ($\eta \ll 1$). Hence, the region of stellar wind collision is much nearer to the OB star than to the WR star ($r_{WR} \gg r_{OB}$).

The form of the contact surface C near the OB star ($r \sim r_{OB}$) is given by (see, e.g., Usov 1992)

$$|\vec{R}_c(\chi)| \simeq r_{OB} \frac{\chi}{\sin \chi} \qquad (3)$$

for $\chi \leq \pi/2$ (here χ is the angle between the radius vector $\vec{R}_c(\chi)$ from the center of the OB star to the point at the contact surface and the line connecting the components of the binary).

At intermediate distances ($r_{OB} \ll r < (P/2)V_{WR}^{\infty}$) from the OB star the contact surface C approaches the conic surface $\tilde{C}$ with angle

$$\theta \simeq 2.1 \left(1 - \frac{\eta^{2/5}}{4}\right) \eta^{1/3} \quad \text{for } 10^{-4} \leq \eta \leq 1 \,. \tag{4}$$

The shock fronts S_1 and S_2 are near the conic surfaces $\tilde{S}_1$ and $\tilde{S}_2$ at $r_{OB} \ll r < (P/2)V_{WR}^{\infty}$ as well. In the case of wide WR+OB binaries, like WR 140, when the fraction of the thermal energy of the hot gas lost by emission in the shock layers is small the angle $\Delta\theta$ between these conic surfaces is $\sim \theta$. In the other case the value of $\Delta\theta$ is smaller than θ and asymptotically approaches zero if this fraction goes to unity.

The contact surface C and two shock fronts S_1 and S_2 are twisted at a distance more than $\sim (P/2)V_{WR}^{\infty}$ due to the orbital rotation and have spiral form (see Fig. 1). Since the orbital velocities in massive binaries are typically much smaller than the terminal velocities we have $(P/2)V_{WR}^{\infty} \gg D$.

Since both $r_{WR} \gg r_{OB}$ and the radius of OB star R_{OB} is , as a rule, essentially larger than the radius of the WR star, in close binaries the gas velocity of OB star wind does not reach the terminal value before the shock S_2.

The velocity of the matter outflow $V_{OB}(r)$ at distance r from the center of the OB star varies from almost zero on the OB star surface to V_{OB}^{∞} for $r > r_{ter}$ (Barlow 1982), where r_{ter} is approximately equal to (3-5) R_{OB}.

If $r_{OB} > r_{ter}$, we have the collision of two winds with terminal velocities and values r_{WR} and r_{OB} are determined by equation (2). If $R_{OB} < r_{OB} < r_{ter}$, the gas flowing out of the OB star does not reach the terminal velocity by the time it enters the shock. In turn, the stellar-wind gas of the WR star is decelerated by the radiation pressure of the OB star while approaching the OB star. In this case, the gas velocities ahead of and near the shocks drop, and the gas temperature behind the shocks drops too (Usov 1990, 1992). If $r_{OB} \leq R_{OB}$, the OB wind is suppressed by the ram pressure of the WR wind, on the side facing the WR stars.

2.3. *Basic equations and boundary conditions*

The set of equations which describes the steady gas flow between the shock wave and the contact surface will be the continuity equation:

$$\mathrm{div}\,(\rho\vec{V}) = 0\,, \tag{5}$$

the momentum equation:

$$\rho(\vec{V}\nabla)\vec{V} = -\nabla p\ , \tag{6}$$

and the energy equation:

$$\rho\vec{V}\nabla(H + |\vec{V}|^2/2) = -Q\ , \tag{7}$$

where ρ is the density of the gas and Q is the energy loss per unit gas volume by radiation.

Since the gas in the shock layer is practically totally ionized, its pressure p and its specific enthalpy H can be expressed as

$$p = (N_e + N_i)kT = \frac{\rho kT}{m_p\mu}\ , \tag{8}$$

$$H = \frac{\gamma}{\gamma - 1}\frac{p}{\rho} = \frac{5}{2}\frac{kT}{m_p\mu} \ , \tag{9}$$

here $N_i = \rho/m_pA$ is the ion density, $N_e = N_iZ$ is the electron density.

The ionized gas heated in the shock layer is emitting mainly due to free-free transitions of electrons in the Coulomb fields of ions at the gas temperature $T > 3 \times 10^6$ K (Gaetz and Salpeter 1983).

Gas parameters ahead of the shock front (index 1) and behind the shoch front (index 2) are related via the Rankin-Hugoniot relations

$$\rho_1 V_1^{(n)} = \rho_2 V_2^{(n)}, \quad p_1 + \rho_1 (V_1^{(n)})^2 = p_2 + \rho_2 (V_2^{(n)})^2 \ ,$$

$$V_1^{(\tau)} = V_2^{(\tau)}, \quad H_1 + \frac{1}{2}(V_1^{(n)})^2 = H_2 + \frac{1}{2}(V_2^{(n)})^2 \, . \tag{10}$$

Indices n and τ denote the normal and tangential components of the vector $\vec{V}$. The condition $V^{(n)}$=0 is met on the contact surface. This condition and the Rankine-Hugoniot relations (10) are the full set of boundary conditions for the set of equation (5)-(9) needed to find the parameters of hot gas in the shock layers.

2.4. *The method of solution*

The set of equations (5)-(9) with the boundary conditions (10) was solved in (Galeev, Pilyugin and Usov 1989; Bairamov, Pilyugin and Usov 1990; Usov 1992) analytically using the method of Chernyi (1961). In this method the ratio of the density of the gas, ϵ, ahead of the shock to that behind it was considered as a small parameter, $\epsilon \ll 1$. If the fraction of the thermal energy of the hot gas lost by emission in the shock layer is small, ϵ is equal to $(\gamma-1)/(\gamma+1) = 1/4$. If the thermal energy losses are essential, the value of ϵ decreases and goes to zero when practically all thermal energy of the hot gas is radiated.

The problem of stellar wind collision was solved in the following way. First, the parameters of the hot gas in the external and internal shock layers were obtained as a function of the form of unknown contact surface. Then the form of the contact surface was found from the equality of the gas pressure on both sides of contact surface.

In the Newtonian approximation, when we neglect the Busemann correction, the equation for the contact surface is given by equation (3). The difference between the analytical equation (3) and the numerical solution for the contact surface with Busemann correction is smaller than 10%. Therefore, to calculate both the parameters of the hot gas in the external and internal shock layers and X-ray emission from the shock layers equation (3) for the contact surface was used (Usov 1992).

3. X-RAYS FROM THE REGION OF STELLAR WIND COLLISION

3.1. *Collision of two stellar winds with terminal velocities*

If a WR + OB binary is wide enough, $r_{OB} > r_{ter}$, the WR and OB winds collide with the terminal velocities, and the fraction of the thermal energy of the hot gas lost by emission in the shock layers is, as a rule, small. In this case,

the expected X-ray luminosity is (Usov 1992)

$$L_{ext} \simeq 8 \times 10^{34} \left(\frac{\dot{M}_{WR}}{10^{-5} M_\odot yr^{-1}}\right)^{1/2} \left(\frac{\dot{M}_{OB}}{10^{-6} M_\odot yr^{-1}}\right)^{3/2} \left(\frac{V^\infty_{WR}}{10^3\, km\, s^{-1}}\right)^{-5/2} \times \left(\frac{V^\infty_{OB}}{10^3\, km\, s^{-1}}\right)^{3/2} \left(\frac{D}{10^{13} cm}\right)^{-1} \ \text{erg s}^{-1} \tag{11}$$

from the external shock layer between the shock front S_1 and the contact surface (see Fig. 1), and

$$L_{int} \simeq 1.3 \times 10^{35} \left(\frac{\dot{M}_{WR}}{10^{-5} M_\odot yr^{-1}}\right)^{1/2} \left(\frac{\dot{M}_{OB}}{10^{-6} M_\odot yr^{-1}}\right)^{3/2} \left(\frac{V^\infty_{WR}}{10^3 km\, s^{-1}}\right)^{1/2} \times \left(\frac{V^\infty_{OB}}{10^3 km\, s^{-1}}\right)^{-3/2} \left(\frac{D}{10^{13} cm}\right)^{-1} \ \text{erg s}^{-1} \tag{12}$$

from the internal shock layer between the shock front S_2 and the contact surface.

The total power of X-ray emission from the region of stellar wind collision is $L_x = L_{ext} + L_{int}$. The X-ray spectra of the shock layers may be roughly approximated by the bremsstrahlung radiation of the uniform totally ionized plasma with the temperature $\sim (0.8-0.9)T(V^\infty_{WR})$ for the external shock layer and $\sim (0.8{-}0.9)T(V^\infty_{OB})$ for the internal shock layer, where T is given by equation (1).

To calculate the parameters of hot gas in the shock layers and the X-ray emission of this gas the values of ϵ and $\eta^{1/2}$ were considered as small parameters. Since the zero and first terms of the series were taken into account only, the accuracy of our calculations is of the order of $(\epsilon^2 + \eta)^{1/2}$, i.e. the accuracy is several tens of percent for $\eta \leq 0.1$ which is typical for WR+OB binaries.

In our consideration of X-ray emission from the region of stellar wind collision we did not take into account the absorption of X-rays in the stellar winds. We can do it for wide WR + OB binaries, $D > 10^{13}$ cm, (Usov 1992) when the sightline to the region of stellar wind collision is passed far enough from the WR and OB stars.

3.2. *Close and very wide binaries*

In a close binary, $r_{OB} < r_{ter}$, both the WR stellar wind and the OB stellar wind have velocities near the shock wave which are less than their terminal velocities (see Section 2.2). To estimate the X-ray emission from the region of stellar wind collision it is necessary to substitute V^∞_{WR} and V^∞_{OB} for V^*_{WR} and V^*_{OB} in equations (11) and (12) (here V^*_{WR} and V^*_{OB} are the gas velocities of the WR and OB stellar winds, respectively, ahead of and near the shocks). Let us discuss briefly the behaviour of the X-ray luminosity, L_x, for a remote observer when the value of r_{OB} varies from r_{ter} to R_{OB}.

At first the X-ray luminosity L_x may increase a few times in comparison with the sum of equations (11) and (12), $L_x \propto (V^*_{WR,OB})^{-1}$. In turn, the gas

temperature in the shock layers drops, $T \propto (V^*_{WR,OB})^2$, and the spectrum of the X-ray emission shifts to the soft region (Usov 1990). Then, if the value of r_{OB} is a few times smaller than r_{ter}, the main portion of this soft X-ray emission is absorbed in the WR and OB stellar winds and the X-ray luminosity is decreased (Luo, McCray and Low 1990; Usov 1990). At $1 \leq (r_{OB}/R_{OB}) \leq 1.2 - 1.3$ the X-ray emission is suppressed practically at all. Hence, it is expected that the X-ray luminosity of a WR + OB binary is as high as possible when $r_{OB} \simeq (0.5-1)r_{ter}$ or $D \simeq (0.5-1)\eta^{-1/2}r_{ter}$.

It is worth noting that some increase of the X-ray flux may be observed near the conic surface $\widetilde{C}$ from more or less close WR + OB binaries for which the X-ray absorption in the stellar winds is essential. The point is that the outflowing plasma in the shock layers is highly ionized, and the X-ray absorption along this surface may be small.

Equations (11) and (12) are valid only if there is temperature equalization between ions and electrons in the shock layers. If there is no such an equalization, the power of the bremsstrahlung emission from the layer is $\sim L(D/D_{eq})^{-1/3}$ at $D \geq D_{eq}$, where L is given by either equation (11) or equation (12) depending on the kind of the shock layers and D_{eq} is the distance between the conponents of the binary at which temperature equalization in the shock layer is broken (Usov 1992). The temperature of electrons which determines the X-ray spectrum is $\propto (D/D_{eq})^{-2/3}$ at $D \geq D_{eq}$.

Among WR + OB binaries, WR 140 is the most powerful X-ray source, $L_x \simeq 4 \times 10^{34}$ ergs s^{-1} (Pollock 1987). It is natural because at the moment of the X-ray observation WR 140 was more or less near the state with $r_{OB} \sim r_{ter}$. The observed value of L_x is in agreement with the X-ray luminosity which is expected from the region of stellar wind collision in WR 140 (Usov 1992).

Except for the X-ray emission generated in the region of stellar wind collision, WR + OB binaries may have an X-ray emission which is inherent in single stars. X-ray emission of single massive stars may be generated due to heating of the outflowing gas to temperatures of about a few million degrees either by a large number of quasi-periodic strong shocks (Lucy and White 1980; Cassinelli and Swank 1983; Owocki and Rybicki 1985) or by the current sheets (Usov and Melrose 1992). From analysis of time variability of X-ray emission from WR + OB binaries it is possible to separate X-ray emission of colliding winds from X-ray emission that is inherent in single stars.

4. GAS COOLING AND DUST FORMATION

In the shocks the gas of stellar winds is compressed but not more than ~ 4 times. If a WR + OB binary is close enough and during the gas motion through the shock layer the main part of the thermal energy of the hot gas is radiated, the degree of the gas compression can increase significantly, i.e. a cold dense gas may be formed. The terminal velocity of the cold gas has to be essentially smaller than V^∞_{WR} and V^∞_{OB}. This cold gas may be heated and accelerated because of its interaction with the WR high-velocity wind.

In the case of long-period binaries like WR 140 even near the periastron passage the fraction of the thermal energy of the hot gas lost by emission is small. At first sight in this case the hot gas outflowing in the shock layer has to expand quasi-adiabatically, and the essential cooling and compression of the gas in the region of the stellar wind collision is impossible. But it is not so. Indeed

the main part of the hot gas in the shock layer expands quasi-adiabatically. However, near the contact surface there is the region where the energy losses may be important and the gas may cool and compress very strongly (Usov 1991). The strong cooling in this region is caused by the slow motion of the gas along the contact surface, such that the gas has ample time to cool. In this case the fraction of the WR wind which may be strongly cooled and compressed in the shock layers is (Usov 1991)

$$\alpha \simeq \eta^2 \left(\frac{\dot{M}_{WR}}{10^{-5}\, M_\odot yr^{-1}}\right)^2 \left(\frac{D}{10^{13}\, cm}\right)^{-2} \left(\frac{V^*_{WR}}{10^8\, cm\, s^{-1}}\right)^{-6} . \tag{13}$$

The characteristic cooling time of the hot plasma via the bremsstrahlung depends on the temperature and the density as $\tau_c \simeq 1.5\times10^{11} N^{-1} T^{1/2}$ s. Taking into account that the external pressure of the hot gas compresses the cooling gas ($N \propto T^{-1}$), we have $\tau_c \propto T^{3/2}$, i. e. the process of cooling near the contact surface is accelerating (thermal instability). The gas near the contact surface may be cooled down to $\sim 10^4 - 10^5$ K, and the density of the cold gas may be as large as $\sim 10^3 - 10^4 \rho_*$, where ρ_* is the gas density before the shock (Usov 1991).

At the distance $r_d \simeq$ a few $\times 10^{15}$ cm from the binary, the cold dense gas can form a dust shell and reradiate the UV radiation in the IR region (Williams et al. 1990, 1992, 1994; Usov 1991).

The value of α is, as a rule, very small at $r_{OB} > r_{ter}$ because of high velosity of the stellar winds and increases very sharply at $r_{OB} < r_{ter}$. When r_{OB} is comparable with R_{OB}, the dynamical gas pressures of both winds ahead of the shocks are decreased, and the gas compression in the shock layers is decreased too. In addition, in close WR + OB binaries with $r_{OB} \sim R_{OB}$ the X-ray absorption inside the shock layers is high, and it can prevent a strong gas cooling in the layers. Therefore, when the value of r_{OB} is somewhere between $\sim r_{ter}$ and $\sim 0.3 r_{ter}$ (say, $r_{OB} \simeq 0.5 r_{ter}$), the most favourable conditions for a strong compression of the gas in the shock layers are realized (Usov 1991).

The long-period WR binaries (WR 48a, WR 125, WR 137, WR 140, and possibly WR 19) with a large enough value of the orbital eccentricity are distinguished among the rest of the WR binaries in that they experience the state with $r_{OB} \sim 0.5 r_{ter}$ in the process of their orbital motion. In this state there is a strong outflow of cold gas, which leads to an IR outburst (Williams et al. 1992, 1994).

5. PARTICLE ACCELERATION AND RADIO AND γ-RAY EMISSION

It is well known that plasma shocks in astrophysical setting can and do accelerate charged particles to high energies (for a review, see Blandford and Eichler 1987 and Ellison and Jones 1991 and references therein). Therefore the strong shocks formed by the colliding stellar winds in WR + OB binaries are very promising as particle accelerators.

Necessary conditions for particle acceleration by a shock wave include the following (Eichler and Usov 1993):

1. *The shock must be collisionless in the absence of an external injection mechanism.* This is typically satisfied if the strength of the magnetic field ahead

of the shock is $B \gg 10^{-6}$ Gauss. Here and below all numerical estimates are given for a typical WR + OB binary (see Section 2.1).

2. *The Ohmic damping rate of Alfven waves must not exceed the maximum growth rate.*

3. *For primary electron acceleration, the shock velocity must considerably exceed the phase velocity of whistler waves propagating normal to the shock.*

Last two conditions holds if $B \ll$ a few Gauss.

All of these constraints on B are typically satisfied by colliding winds in WR + OB binaries. Hence the region of stellar wind collision in these binaries may be a strong source both high energy particles and nonthermal radiation generated by these particles.

The maximum electron energy is limited by ion-neutral wave damping and by inverse Compton losses (Bell 1978). The maximum energy allowed by ion neutral damping should be well above 100 Gev and does not play an important role.

The upper limit on the Lorentz factor of electrons due to inverse Compton losses can be shown, assuming a quasi-parallel shock geometry, to be given by (Eichler and Usov 1993)

$$\Gamma^2_{\max} \leq \frac{3\pi eBcr^2_{_{OB}}}{\lambda\sigma_{_T} L_{bol}} \left(\frac{V^{\infty}_{_{WR}}}{c}\right)^2 \simeq 3\times 10^8 \eta \left(\frac{B}{\mathrm{Gauss}}\right) , \tag{14}$$

with approximate equality obtaining in the absence of any other, stronger limits. Here $L_{bol} \simeq 10^{39}$ ergs s^{-1} is the bolometric luminosity of the OB star, $\sigma_{_T}$ is the cross-section of Thomson scattering, e is the electron charge and $\lambda \simeq 3$ is the ratio of mean free path to gyroradius.

Given the constraints of B discussed above, the energy of electrons $E_{\max} = \Gamma_{\max} mc^2$ is enough to generate synchrotron radio emission at the frequencies of which nonthermal radio emission from WR + OB binaries has been observed (Florkowski and Gottesman 1977; Becker and White 1985; Abbott et al. 1986; Felli and Massi 1991).

A differential energy spectrum expected for relativistic electrons accelerated in the region of stellar wind collision is $N(E) \propto E^{-\beta}$, where $N(E)dE$ is the number of high energy electrons per unit volume with total energy E in the interval dE and $\beta \simeq 2$. The spectrum of synchrotron radiation generated by relativistic electrons with this energy spectrum is $S(\nu) \propto \nu^{-\gamma}$, here $S(\nu)$ is the flux of radiation at the frequency ν and $\gamma = (\beta-1)/2 \simeq 0.5$ is a spectral index.

Typically, only a small fraction of the energy of accelerated electrons are converted to radio emission before the flow convects them out of the colliding wind region.

From equation (3) we can get the characteristic size of nonthermal radio emisson

$$l^{rad} \simeq 2R_c(\pi/2) \simeq \pi r_{_{OB}} . \tag{15}$$

Stellar winds outflowing from the WR and OB stars are opaque to free-free absorption. A typical radius of the radio photosphere at the frequency of a few GHZ for WR stars is $R^{rad}_{_{WR}} \simeq$ a few times 10^{14}cm (Wright and Barlow 1975). The value of this radius for OB stars, $R^{rad}_{_{OB}}$, is approximately an order of magnitude smaller than $R^{rad}_{_{WR}}$. Hence, in the case of WR and OB stars the radius of their radio photosphere is of the order of hundred or more stellar radii.

Radio emission from the colliding wind region may be observed at the frequency ν only if the time $R^{rad}_{_{WR}}/V^{\infty}_{_{WR}}$ during which the gas outflowing from the WR star with the velocity $V^{\infty}_{_{WR}}$ reaches the radius of the radio photosphere $R^{rad}_{_{WR}}$ is of the order of or smaller than the time which is necessary for the WR+OB binary to turn on the angle $2\theta + \Delta\theta \simeq 3\theta$ (see Fig. 1), i.e.

$$\frac{R^{rad}_{_{WR}}}{V^{\infty}_{_{WR}}} \leq \frac{3\theta}{2\pi} P \quad \text{or} \quad P \geq P_{cr} = \frac{2\pi}{3\theta} \frac{R^{rad}_{_{WR}}}{V^{\infty}_{_{WR}}} \simeq 13\eta^{-1/3} \left(\frac{\nu}{5\,\mathrm{GHz}}\right)^{-2/3} \text{ days}\,. \quad (16)$$

For a typical WR+OB binary (see Section 2.1) the value of P_{cr} is of the order of a month when the frequency of observation is a few GHz.

If $P < P_{cr}$ nonthermal radio emission from the region of stellar wind collision in the WR+OB binary cannot be observed because it is screened by the WR wind.

Striking variations of radio emission from remarkable WR binary WR 140 were observed (Florkowski and Gottesman 1977; Becker and White 1985; Abbott et al. 1986). This time variability and the other observational data on radio emission of WR 140, such as luminosity, spectrum, the size of nonthermal radio source, etc., may be explained by a model in which its nonthermal radio emission is generated at the site of stellar wind collision (Eichler and Usov 1993).

Gamma-ray emission can be attributed to either inverse Compton emission or $p-p$ collisions followed by pion decay. In the former case, the seed photons would presumably be the processed UV radiation from the OB stars. A high-energy tail of the inverse Compton spectrum of γ-rays may exist up to $\sim 10^3$ MeV (Eichler and Usov 1993).

Considerations of shock acceleration theory suggest that the WR 140 system may be a strong source of γ-rays (Eichler and Usov 1993). The γ-ray flux has to increase essentially near the periastron passage. Recently, the hard X-ray and soft γ-ray emission from WR 140 was observed by the OSSE detector aboard the CGRO (Hermsen et al. 1994).

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